The First Scientific Results from the Pierre Auger Observatory

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Abstract.
The southern site of the Pierre Auger Observatory is under the construction near Malargue in Argentina and now more than 60% of the detectors are completed. The observatory has been collecting data for over 1 year and the cumulative exposure is already similar to that of the largest forerunner experiments. The hybrid technique provides model-independent energy measurements from the Fluorescence Detector to calibrate the Surface Detector. Based on this technique, the first estimation of the energy spectrum above 3 EeV has been presented and is discussed in this paper.

The Pierre Auger Observatory is the largest cosmic ray detector ever built to study the Ultra-High Energy Cosmic Rays (UHECR) with unprecedented statistics and high precision [1]. In particular, it is important to address whether the cosmic-ray spectrum continues beyond 10^{20} eV. Due to the interaction with microwave background photons, a steepening is expected around 10^{20} eV in the energy spectrum if the sources are distributed uniformly throughout the Universe. This conclusion is independent of the composition of the UHECR's.

Recent measurements of the energy spectrum by the AGASA which used surface detector (SD) array [2] and the HiRes which is using fluorescence detector (FD) [3] have yielded conflicting results. There are serious limitations in the use of only the SD or the FD alone to measure the primary spectrum. The SD provides high event statistics with high efficiency and robust exposure estimation. The SD energy estimation, however, traditionally relies on Monte-Carlo simulations which require assumptions about the hadronic-interaction model and the primary-chemical composition. On the other hand, the FD provides a calorimetric energy measurement but the estimation of the exposure has a comparatively large uncertainty relative to the SD.

Based on one year operation of a portion of the Pierre Auger Observatory, the first scientific results were released this summer concerning the upper limit of the UHE gamma ray flux [4], anisotropy of the arrival directions [5], and the energy spectrum [6]. The cumulative exposure, 1750 km^2-sr-yr, is similar to those achieved by the largest forerunner experiments. Statistical uncertainties are still too large to draw any firm conclusions ether rejecting or confirming results obtained by previous experiments. However, there is an important step achieved in these results. The Pierre Auger Observatory was designed as a hybrid detector to observe the shower particles at ground level by the SD and the associated fluorescence light generated in the atmosphere by the FD. Combining the strengths of the SD and the FD, we have developed a reliable estimate of

the primary energy spectrum using the full SD exposure without making assumptions about the primary masses or hadronic model.

The southern site of the Pierre Auger Observatory is now under construction on an Argentinian pampa (35° S, 69° W, 1400 m.asl, 875.5 g/cm^2). The SD consists of 1600 water Cherenkov tanks planed on a triangular 1.5 km grid covering 3000 km^2 area with 2π sky coverage. The construction of the Southern site is now 60% complete. The whole area of the SD will be overlooked by an FD from 4 sites. Each FD site has 6 telescopes and each telescope has a $30^\circ \times 28.6^\circ$ field of view with 1.5° pixel size. Three FD sites are completed and operating now and one is under construction.

The events recorded in the SD are reconstructed using the arrival time and the signal size from the shower particles reaching the detectors. The magnitude of the signal at 1 km from the shower axis, S(1000) in Vertical Equivalent Muon (VEM), is estimated from the Lateral Distribution Function fit as a size parameter of the shower [7]. Two cosmic rays of the same energy, but incident at different zenith angles, will yield different values of S(1000) due to an attenuation of the shower in the atmosphere. This attenuation is measured by the well-established technique of the constant intensity cut (CIC) method. The principle of this method is that the nearly isotropic intensity of cosmic rays means that the integrated intensity above any given energy must be the same at all zenith angles (θ degree). One finds the S(1000) at every zenith angle that corresponds to a single primary energy by varying S(1000) at each zenith angle to obtain a fixed integral intensity. Based on this method, the zenith angle dependence of S(1000), the CIC curve is obtained as

$$S(1000)_{38^\circ} = \frac{S(1000)_\theta}{1.049 + 0.0097\theta - 0.00029\theta^2} \tag{1}$$

where $S(1000)_{38^\circ}$ VEM is S(1000) adjusted to $\theta = 38^\circ$. (The median zenith angle of the showers is 38°.)

The link between $S(1000)_{38^\circ}$ and the primary energy can be established using data from the FD. On dark dry nights, the fluorescence signals are observed simultaneously with the SD events. The fit to the FD-energy as a function of $S(1000)_{38^\circ}$ is

$$log(E) = -0.79 + 1.06 log(S(1000)_{38^\circ}) \tag{2}$$

where E is the FD-energy in EeV.

The events detected by the SD are selected as follows: The estimated energy must be greater than 3 EeV because detection efficiency is saturated (nearly 100%) above this energy. The zenith angle of the arrival direction must be smaller than 60°. And the event must fall within a well-defined fiducial area. The estimate of the SD exposure is simple. The fiducial area is monitored in the trigger system so that exposure is calculated as the time integration of the aperture given by the fiducial area and the 60° zenith-angle limit. The spectrum is then obtained by dividing the number of events in given energy intervals by the exposure as shown in Figure.1.

The systematic uncertainty of the energy spectrum comes mainly from the energy assignment. In the estimation of the FD-energy, there are several uncertainties which include the fluorescence yield (15%), missing energy carried by high-energy muons and neutrinos (4%), the absolute calibration of the FD telescopes (12%), and atmospheric

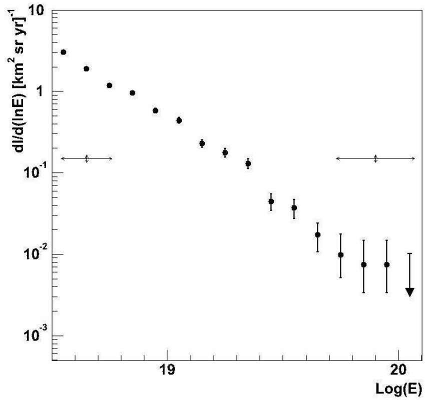

FIGURE 1. Estimated spectrum. Plotted on the vertical axis is the differential flux. Error bars on points indicate statistical uncertainty or 95% CL upper limit. Systematic uncertainty is indicated by double arrows at two different energies [6].

condition (10%). Overall the uncertainty of the FD-energy is about 25%. These systematic errors will be reduced significantly in a year with completion of the FD calibration and the measurement of the fluorescence yield in laboratories . The statistical uncertainty in Equation.2 causes additional energy-dependent systematic uncertainty in the energy estimation. This uncertainty is dominant to the systematic error in the highest energy and will automatically shrink with the rapidly-increasing hybrid statistics. The total systematic error is indicated in the Figure.1.

It should be noted that this energy spectrum was measured in the southern sky which could differ from that of northern sky measured in the previous experiments. The energy scale based on the FD measurements is systematically lower than that from an SD analysis that uses QGSJetII simulations with proton primaries. The difference is similar to the conflicting energy scales of the HiRes and the AGASA collaborations. The exposure of the southern observatory is expected to increase by a factor of 5$\sim$7 over the next two years. With completion of the FD calibration, the statistical and systematic errors will shrink accordingly, permitting a study of spectral features and the energy scale.

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